Investigation of Off-Axis Detection and Classification in Bottlenosed Dolphins

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ABSTRACT - **Mine-hunting dolphins in the Navy's Marine Mammal Systems (MMS) are likely to initially encounter targets on the edge of the maximum response axis (MRA) of the echolocation beam. Understanding how Fleet dolphins perform their search-and-report tasks will provide valuable information toward the enhancement of Navy mine countermeasure (MCM) signal processing approaches that utilize off-MRA acoustic returns.**

Current research to this end will contribute toward development of biomimetic sonar systems that are robust in detecting and classifying targets encountered in real-world search conditions where detection, localization, and identification of those targets prior to selecting appropriate MCM actions is required. This paper addresses ongoing investigations of the ability of an echolocating dolphin to detect and classify targets that are presented off the main axis of its transmit and receive sonar beam.

I. INTRODUCTION

SSC-San Diego has been conducting research with dolphins for over 40 years. Initial studies began in 1959 with investigations of hydrodynamic properties of the Atlantic bottlenose dolphin (*Tursiops truncatus*). Since then, SSC-San Diego has conducted research with a variety of marine mammals. Research and development has been directed towards two major goals: (1) training marine mammals to perform tasks important to Navy missions, and (2) building hardware based on the natural echolocation capabilities of the dolphin [1].

Dolphin echolocation has evolved over 50 million years under selection pressures imposed by a specific littoral niche. Its complexity and effectiveness in allowing for detection and classification of objects within that niche has useful application to Naval MCM objectives. In these environments, mine-hunting dolphins are likely to first encounter targets on the edge of their sonar beam during a search. It is unknown, however, if target classification is possible from the off-axis information alone, or whether a more centrally focused interrogation is necessary.

II. DOLPHIN ECHOLOCATION

Fleet systems use bottlenose dolphins to find and mark mines because they have enhanced acoustic sensors, are mobile in open waters and consistently out-perform all available artificial mine countermeasures (MCM) systems in the Shallow Water (SW) and Very Shallow Water (VSW) littoral environment. The ability to outperform artificial systems is due to the performance of a focused sound generator that is co-evolved with an auditory system specialized for the reception and processing of pulsed, broadband acoustic signals. These adaptations collectively form the basis of dolphin biosonar, or echolocation.

Dolphins can use their biological sonar (biosonar) to discriminate between objects differing in size, structure, shape, and material composition [1]. Dolphins can detect the presence of small (7.62 cm stainless steel) spheres at distances up to 119 m [4]. They can discriminate between aluminum, copper, and brass circular targets; between circles, squares, and triangular targets; and can recognize aspect-dependent objects at random orientations [2,3,4]. The generation of echolocation clicks has been shown to be under voluntary control of the dolphin [5]. The existence of a voluntary mechanism implies that the dolphin can learn to select optimum source levels, center frequencies, and bandwidth required for target detection and recognition. Additional support for such a learning mechanism has been shown through signal variation observed in echolocation click structure that occurs under different tasks [6].

A. Emitted Signal

Bottlenose dolphin echolocation signals are broadband clicks, with peak energy at frequencies ranging from 40 to 130 kHz and peak source levels of up to 220 dB re: 1μPa. The ultrasonic click series emerges from the rounded forehead, or melon, as a highly directional sound beam with 3 dB (half power) beam widths of approximately 10° in both the vertical and horizontal planes [7].

B. Received Signal

The echo from an ensonified target can have a complex acoustic structure. Echo characteristics include extended duration, irregular envelopes, and various other target modulation effects that are effected by the environment within which they are collected. Exactly how the animal collects target size, shape, and composition information from these echoes and what parts of the signal comprise the "important" pieces of information is as yet not fully known. However, it is known that dolphins have an extended hearing capability, and, though the auditory system is basically mammalian, important anatomical adaptations exist that presumably contribute to this capability.

Given the current understanding of dolphin biosonar, the next logical step is to develop prototype biomimetic sonar that incorporates existing knowledge of the dolphin sonar system in a testable hardware platform. This hardware would allow us to test and develop models and algorithms based on our experimental results. This approach of transitioning experimental results to working models is presented in other papers at this meeting that discuss the development of the Biosonar Measurement Tool (BMT), and the incorporation of the BMT data into a Dolphin-Based Sonar (DBS - also presented at this meeting) [8,9]. The study reported here attempts to add another piece of information to the understanding of dolphin-based biosonar development.

III. EXPERIMENTAL DESIGN AND PROCEDURE

A. Apparatus and Electronics

This study involves a dolphin detecting two different targets (cylinder and sphere) presented off the maximum response axis (off-MRA) both to the left and right. Data are collected using standard psychoacoustic experimental methods, which provide

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14. ABSTRACT

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control over extraneous variables, thereby increasing inferential strength of the study.

Outgoing echolocation clicks and echo pairs are digitized and stored to a PC for acoustic characterization using a high-speed IBM compatible computer system with an ICS 645 A/D card (16 MB/sec sample rate, 5 sec per trial, resulting in storage on the hard drive of approx. 96MB per trial). Twenty-four calibrated, spatially separated monitor hydrophones, with 24 analog in-line filter-amplifiers (sampled at 312.5 kHz sample rate) are arranged in a hemispherical support web (Fig. 1) positioned approximately 1.0 m in front of the animal. These hydrophones comprise the emitted signal receiver array (rec. array)

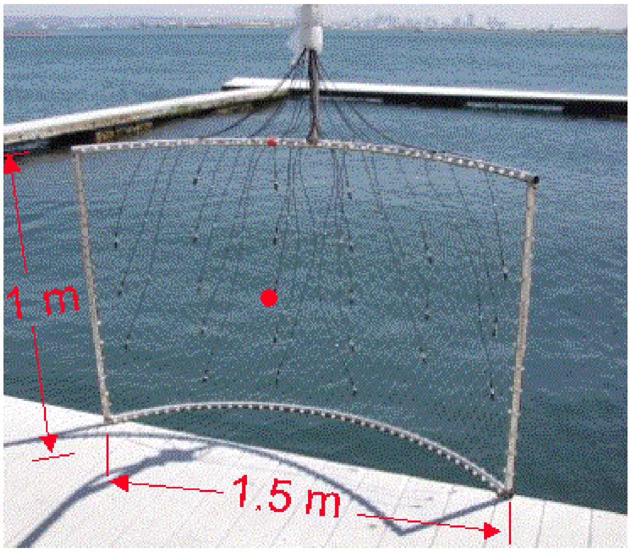

Fig. 1. Picture of the hydrophone array frame and nylon web used to support the 24 hydrophones (Reson TC 4016). The lines at the top of the frame are the signal leads of the hydrophones.

The test facility is located in San Diego Bay in approximately 35 feet of seawater. A diagram of the animal test pen and overall layout of the test apparatus are illustrated in Fig. 2.

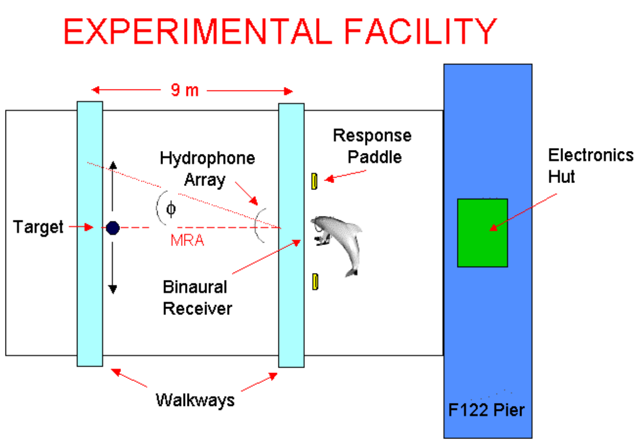

Fig. 2. A diagram of the test facility showing the relative positions of the dolphin, target (shown on-MRA), rec. array, and response manipulanda to the target range (9.0 m). The electronics for digitizing the signals and scheduling experimental trials are housed in the electronics hut.

The animal is stationed on a custom-fit bite plate (mouthpiece) that assures a fixed orientation of the head in line with the major long axis of the body (Fig. 3). This position defines the MRA of the animal's transmit and receive beams. The dolphin-emitted signals are collected using the rec. array. A biologically inspired binaural receiver located beneath the animal collects echoes from targets when they are in line with the animal (on-MRA), or placed at various displacement increments to the animal's left and right (off-MRA).

Fig. 3. The bite plate stationing device and the binaural receiver mounted directly below and in line with the animal's MRA. The animal is trained to bite on the soft rubber insert (fitted to it's rostrum shape) and hold during echolocation.

The binaural receiver consists of two high gain, directional hydrophones that are modeled after the dolphin auditory system for the purpose of receiving dolphin-generated echoes and ambient sound data. These hydrophones have beam widths comparable to behaviorally measured dolphin receive beam patterns [10]. The biomimetic receivers' spacing -- 12.5cm -- approximates the distance between the dolphin's inner ears. The higher gain and directivity index associated with the binaural receiver allows for the collection of return echoes from targets that have small target strength (such as the cylinder and sphere targets employed) out to ranges in excess of 30 m.

The target set for this animal consists of a cylinder and sphere target. The cylinder is 18 cm in length and 7.63 cm in outside diameter. The sphere is 18 cm in diameter and water-filled (Fig. 4).

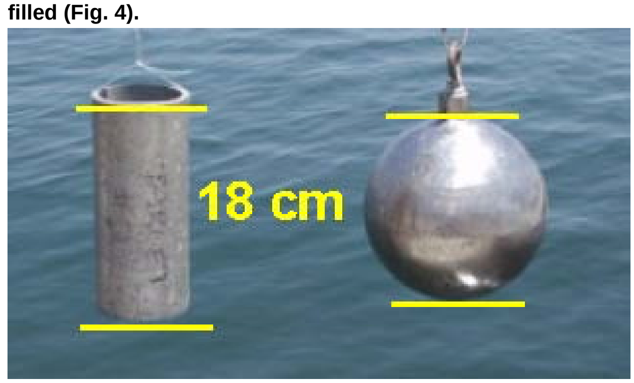

Figure 4. The target set for the detection experiment

B. Experimental Procedure for Off-MRA Detection

The animal is trained to station on the bite plate apparatus and await the removal of a screen that blocks his echolocation to the target field. During his wait, if the trial is designated as *present*, one of the targets is placed at the depth corresponding to his MRA (0° position) or at a predetermined off-MRA position. If the trial is designated as *absent*, no target is presented. A trial

is initiated by raising the visually- and acoustically-opaque screen, whereupon the animal is allowed to echoically investigate the down-range environment from his fixed position for 5 sec. During this investigation, his vision is blocked by a fixed barrier that is only echoically transparent (located behind the removable screen). To report a target *present,* the animal swims to a response paddle within 5 sec of the screen removal.

To report a target *absent,* he remains on the bite plate for the trial duration (5 sec). Correct reporting for both target present (on MRA or at some off-MRA position) and target absent trials are reinforced with fish. Incorrect reporting is never reinforced. An equal number of target present and absent trials are conducted every session in a randomized order such that the first-order conditional probability of a target present or absent trial is 0.50.

In the final portion of this experiment, eight threshold estimations of off-MRA distance to the right and left (four per target – two right, two left) will be conducted using an up/down staircase method in 1-2^o off-MRA increments. The sessions will start with ten warm-up trials in which the target will be placed on-MRA for the present condition. For the ensuing present trials, the target will be placed successively further off-MRA in one direction (left or right). OA distance for each succeding present trial will be determined by the animal's performance on the previous present trial: distance will increase by 1.0^o after every hit (correct detection), and decrease by 1.0^o after every miss. The average off-MRA distance after ten directional changes (hit followed by miss, and vice versa) will determine the animal's estimated threshold.

IV. INITIAL RESULTS AND DISCUSSION

Preliminary off-MRA behavioral and acoustic data for the two targets differing in shape and target strength have been obtained. Since this is an ongoing study, available results to date will be presented. Reported threshold results represent only a rough bracket of what the final estimates may be once the previously described titration sessions are conducted.

Animal detection performance for the sphere and cylinder targets as a function of off-MRA position (angular displacement) and direction (left/right) has been used to bracket detection thresholds. A total of 429 off-MRA trials, ranging from 1-30 ^{o} to the left and 1-21^V to the right, have been conducted. The subject performed at 94% correct overall. Preliminary results indicate the sphere target OA threshold to the animal's right is approximately 18^o and about 23^o to the animal's left. However, for the cylinder target, the detection threshold is about 20^o to the left but only about 10^o to the right.

Several possibilities can explain the unusual off-MRA detection threshold for the cylinder to the right. The subject is known to have a high frequency hearing loss in both ears, and a mid-range frequency loss in the right ear [11]. Furthermore, because the cylinder is suspended along the long vertical axis of the target, it is only aspect-independent as long as that vertical orientation is maintained. Subsequent observation of the returns from the cylinder target showed that at times (during wave action) the target was displaced from the vertical axis, resulting in considerable target strength variations from click-to-click emitted during that displacement. It is suspected that this variation in vertical orientation resulted in a change of target strength as the target was displaced from the vertical axis by random wave and current action, a phenomenon to which the aspect-independent sphere target would not be subject. Therefore, difficulty with the weaker target, especially as off-axis distance to the right increases, is not unexpected. Continuing work is planned with target sets that will not produce these uncontrolled target strength variations, and with a dolphin that has normal hearing. Comparison of angular displacement thresholds between animal subjects may evidence as yet unknown underlying emergent properties that may allow additional conclusions to be made.

Analyzing changes in echolocation behaviour during the experiment is providing additional insight into the bracketed detection threshold results. Inspection of click production by target type (sphere, cylinder), off-MRA distance (1-6 ^{o}, 7-12^o, 13-18 ^{o}, 19-24 ^{o}, 25-30 ^{o}), and direction (left/right) shows significant differences in the number of clicks produced as a function of target type (one-way ANOVA; $F(1,751)=138$, $p<0.0001$) and off-MRA distance (one-way ANOVA; $F(4,410)=22$, $p<0.0001$), but not by direction. Specifically, the animal emitted more clicks when the cylinder was present (Fig. 5) and as off-MRA distance increased (Fig. 6). In dolphin echolocation, the click count has been shown to be an indicator of increased echolocation effort [12]. These results therefore support the notion that the cylinder is generally more difficult to detect than the sphere, and that detection becomes more difficult as the boundaries of the animal's beam width are approached.

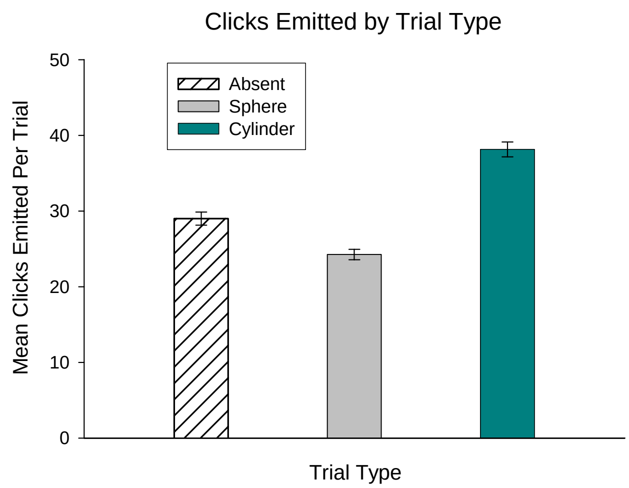

Fig. 5. Mean number of clicks produced per trial as a function c sphere (n=398), cylinder (n=355), and absent (n=694) trial type are shown. Sphere and cylinder data include trials in which th target was presented on-MRA (0º). Mean click production c absent trials are shown for baseline comparison purposes. Erro bars are standard error of the mean.

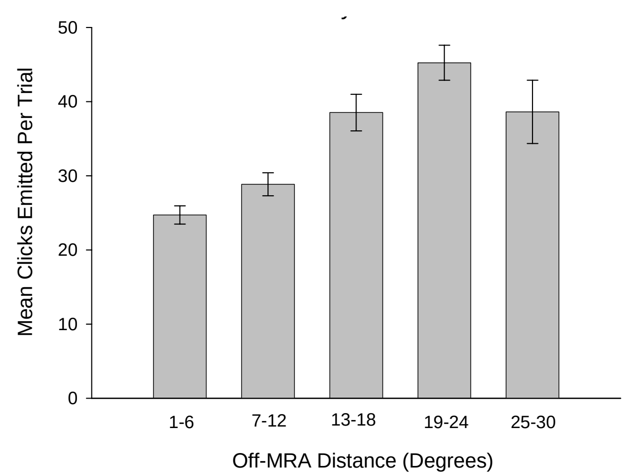

Fig. 6. Mean number of clicks produced per trial as a function of off-MRA distances 1-6º (n=140), 7-12º (n=117), 13-18º (n=60), 19-24º (n=85), 25-30º (n=13) are shown. Data included in each of the five azimuth ranges was pooled from 7 sub-positions within each range. Error bars are standard error of the mean.

Presently we have begun to analyze the placement of the energy peak of each click in relationship to the rec. array grid. This placement is illustrated in Fig. 7, which presents the normalized peak energy for each click in the train (labeled 1-23) across the array area. This analysis is ongoing to assure that all the emitted clicks are placed within the dimentional area covered

by the array of hydrophones. Fig. 7 illustrates that most, if not all, of the emitted clicks are being captured with the array.

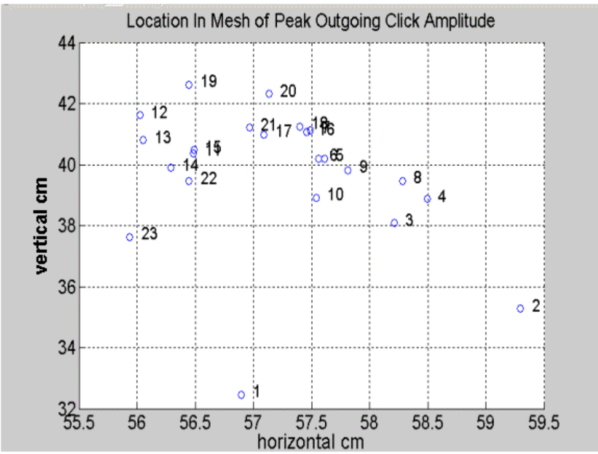

Fig. 7. Shown is a train of 23 clicks. Each click's peak energy is plotted in relationship to the normalized area of the collection array and labeled with its production number.

V. SUMMARY

As this is an ongoing study, we are still developing and refining our approach and data analysis. We plan to continue this study with a final set of targets which are aspect-independent (spheres) and which can be manipulated for target strength (sphere diameter – sm, med, lg) and can also be discriminable within the same target strength category (various fluid fillings, yielding different inter-echo spacial highlight structure). A second subject has also been introduced and his hearing (in both ears) is currently being tested. Assuming he has normal hearing, he will be trained for this task using the fluid-filled sphere target sets. We will estimate off-MRA detection thresholds as a function of target strength and then collect and analyze off-MRA discrimination data.

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